Direct Quark Mechanism for Weak $\Lambda N \leftrightarrow NN$ Processes

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Two body weak processes $\Lambda N \leftrightarrow NN$ are studied from the viewpoint of quark substructure of baryons. They can be studied in nonmesonic weak decays of hypernuclei and also hyperon production in the NN scattering. The direct quark mechanism in contrast to the one-pion exchange mechanism is shown to give sizable $\Delta I = 3/2$ contribution in the $J = 0$ channel. Nonmesonic decay rates of ${}^4_\Lambda$H, ${}^4_\Lambda$He, and ${}^5_\Lambda$He agree with the current experimental data fairly well. Especially the n/p ratio is enhanced by the direct quark contribution. The cross sections for $pn \to \Lambda p$ scattering are studied in the quark cluster model approach.

1. Introduction

Recent experimental and theoretical studies of weak decays of hypernuclei have generated renewed interest on nonleptonic weak interactions of hadrons. A long standing problem is the dominance of $\Delta I = 1/2$ amplitudes, called the $\Delta I = 1/2$ rule, in the strangeness changing transitions. Nonleptonic decays of kaons and Λ, Σ hyperons are dominated by the $\Delta I = 1/2$ transition but it is not clear whether this dominance is a general property of all nonleptonic weak interactions. In fact, the weak effective interaction which is derived from the standard model including the perturbative QCD corrections contains a significantly large $\Delta I = 3/2$ component[1]. It is therefore believed that nonperturbative QCD corrections, such as hadron structures and reaction mechanism are responsible for suppression of $\Delta I = 3/2$, and/or enhancement of $\Delta I = 1/2$ transition amplitudes.

From this viewpoint, decays of hyperons inside nuclear medium provide us with a unique opportunity to study new types of nonleptonic weak interaction, that is, two- (or multi-) baryon processes, such as $\Lambda N \to NN$, $\Sigma N \to NN$, etc. These transitions consist the main branch of hypernuclear weak decays because the pionic decay $\Lambda \to N\pi$ is suppressed due to the Pauli exclusion principle for the produced nucleon.

A conventional picture of the two-baryon decay process, $\Lambda N \to NN$, is the one-pion exchange between the baryons, where the $\Lambda N\pi$ vertex is induced by the weak interaction[2]. In $\Lambda N \to NN$, the relative momentum of the final state nucleons is about 400 MeV/c, much higher than the nuclear Fermi momentum. The nucleon-nucleon interaction at this momentum is dominated by the short-range repulsion due to heavy meson exchanges and/or to quark exchanges between the nucleons. It is therefore expected that

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the short-distance interactions will contribute to the two-body weak decay as well. Exchanges of K, ρ, ω, K^* mesons and also correlated two pions in the nonmesonic weak decays of hypernuclei have been studied[3,4] and it is found that the kaon exchange is significant, while the other mesons contribute less[4].

Several studies have been made on effects of quark substructure[5–7]. In our recent analyses[7,8], we employ an effective weak hamiltonian for quarks, which takes into account one-loop perturbative QCD corrections to the W exchange diagram in the standard model[1]. It was pointed out that the $\Delta I = 1/2$ part of the hamiltonian is enhanced during downscaling of the renormalization point in the renormalization group equation. Yet a sizable $\Delta I = 3/2$ component remains in the low energy effective weak hamiltonian. We proposed to evaluate the effective hamiltonian in the six-quark wave functions of the two baryon systems and derived the "direct quark (DQ)" weak transition potential for $\Lambda N \to NN$[7,8]. Our analysis shows that the DQ contribution largely improves the discrepancy between the meson-exchange theory and experimental data for the ratio of the neutron- and proton-induced decay rates of light hypernuclei. It is also found that the $\Delta I = 3/2$ component of the effective hamiltonian gives a sizable contribution to $J = 0$ transition amplitudes. Unfortunately, we cannot determine the $\Delta I = 3/2$ amplitudes unambiguously from the present experimental data[9].

2. Direct Quark Transition Potentials

The DQ transition takes place only when Λ overlaps with a nucleon in hypernuclei and therefore predominantly in the relative S-states of ΛN systems. The two-body transition potentials for the initial $\Lambda N(L = 0)$ and the final $NN(L = 0, 1)$ states are computed in the DQ mechanism and are compared with those in the one-pion exchange (OPE) mechanism. Because of quark antisymmetrization effects, the transition potential contains nonlocal components and as the transition may break the parity invariance, it also contains derivative terms. The general form of the transition potential is

$$\begin{aligned} V^{\ell\ell'}_{ss'J}(r, r') &= \langle NN : \ell' s' J | V(\vec{r}', \vec{r}) | \Lambda N : \ell s J \rangle \\ &= V_{loc}(r)\, \frac{\delta(r - r')}{r^2} + V_{der}(r)\, \frac{\delta(r - r')}{r^2} \partial_r + V_{nonloc}(r', r) \end{aligned} \qquad (1)$$

Fig. 1(a) shows the local part of the DQ and OPE potentials and Fig. 1(b) shows the nonlocal part of the DQ potential for the $\Lambda p(^1S_0) \to np(^1S_0)$ transition. It can be seen in the local potential that the DQ is dominant at short distances, $r < 1.4$ fm, while the OPE in the region $r < 2$ fm is modified strongly by the form factor introduced according to [10]. Both the local and nonlocal potentials show that $\Delta I = 3/2$ contribution is significant. Such strong violation of the $\Delta I = 1/2$ dominance takes place in $J = 0$ transitions, $\Lambda N(^1S_0) \to NN(^1S_0)$ and $\Lambda N(^1S_0) \to NN(^3P_0)$.

Because the OPE potential is determined phenomenologically, the relation between DQ and OPE is not trivial. In order to check the consistency, we relate the $\pi N \Lambda$ coupling constant to a baryon matrix element of the weak hamiltonian for quarks by using the chiral property. In the soft-pion limit, the soft-pion theorem leads to[11]

$$\lim_{q\to 0} \langle \pi^0(q) n | H_W | \Lambda \rangle = \frac{i}{f_\pi} \langle n | [Q_5^3, H_W] | \Lambda \rangle \qquad (2)$$

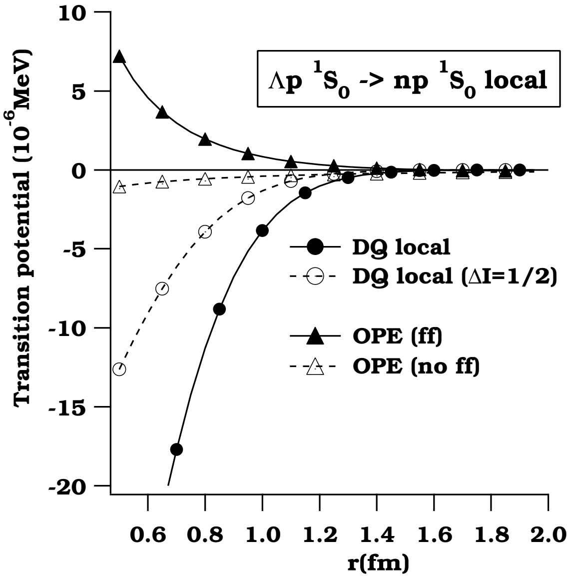

Figure 1. The local part of the $\Lambda N\,^1S_0 \to NN\,^1S_0$ transition potential.

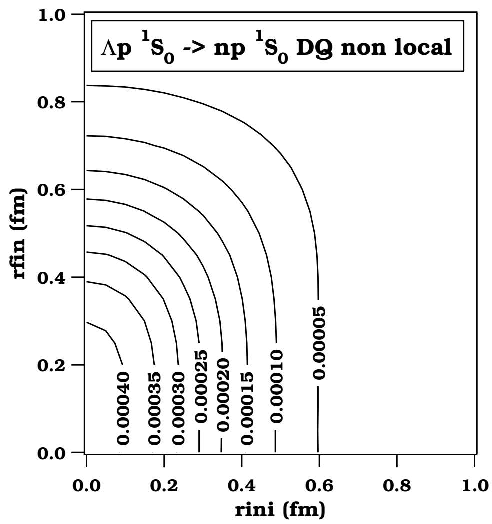

Figure 2. Contour plot of the DQ nonlocal transition potential.

where Q_5^3 is the third component of the axial charge operator. The weak hamiltonian H_W consists only of left-hand currents and the flavor-singlet right-hand currents, and therefore satisfies $[Q_5^3, H_W] = -[I^3, H_W]$, where I^3 is the third component of the isospin operator. Taking the parity conserving part, we obtain[11]

$$\lim_{q\to 0}\langle \pi^0(q) n | H_{PV} | \Lambda\rangle = \frac{-i}{2f_\pi}\langle n | H_{PC} | \Lambda\rangle \tag{3}$$

The LHS of this equation is proportional to the effective $\Lambda N\pi$ weak coupling constant, defined by

$$H_{eff} = i g_w \bar{\psi}_n (1 + \lambda\gamma^5)\pi^0\psi_\Lambda \tag{4}$$

where the phenomenologically determined value of the coupling constant is $|g_w| = 2.3 \times 10^{-7}$ (dimensionless). The RHS of eq.(3) can be evaluated by using the present quark model. Then using the Goldberger-Treiman relation we obtain

$$g_w = g_{\pi NN}\frac{\langle n|H_{PC}|\Lambda\rangle}{2M_N g_A} = -3.5 \times 10^{-7} \tag{5}$$

in our quark model. Here $g_{\pi NN}$ $(= -13.26)$ is defined for

$$H_{\pi NN} = g_{\pi NN}\bar{\psi}_N i\vec{\tau}\cdot\vec{\pi}\gamma^5\psi_N \tag{6}$$

This value is about 30% larger than the phenomenological one. The reason for the over-estimation may reside in the soft-pion assumption as well as in the approximation of the baryon wave functions, that is, the orbital quark wave functions of Λ and n are assumed

to have the same Gaussian form. However, by this estimate we can determine the relative phase of the phenomenological $\Lambda N\pi$ coupling constant and the weak quark hamiltonian. Namely, the product of g_w and $g_{\pi NN}$ in the OPE potential must be positive in order to be consistent with the weak hamiltonian we employ.

Note that the single baryon matrix element $\langle n|H_{PC}|\Lambda\rangle$ has no contribution from the $\Delta I = 3/2$ part of H_W and therefore eq.(3) guarantees the $\Delta I = 1/2$ dominance. In fact, the same argument leads to the $\Delta I = 1/2$ rule for the pionic decays of hyperons as all the single baryon matrix elements, such as $\langle p|H_{PC}|\Sigma^+\rangle$, $\langle\Sigma^0|H_{PC}|\Xi^0\rangle$, have no $\Delta I = 3/2$ contribution if we assume a valence quark picture for the baryon according to [12]. The soft-pion limit also predicts that the $\Sigma^+ \to n\pi^+$ decay is not allowed because the transition from $\Sigma^+(I_3 = +1)$ to $n(I_3 = -1/2)$ is possible only through the $\Delta I = 3/2$ weak hamiltonian. Indeed, $\Sigma^+ \to n\pi^+$ is strongly suppressed experimentally.

3. Nonmesonic Weak Decay of Light Hypernuclei

In [7,8], we calculated the nonmesonic decay rates of ${}^5_\Lambda$He, ${}^4_\Lambda$He, and ${}^4_\Lambda$H in the DQ and OPE mechanisms. The S-shell hypernuclei are most suitable for the study of the microscopic mechanism of the weak decay as their wave functions are relatively simple and contain only $\Lambda N(L = 0)$ states. They also enable us to select spin-isospin components for the weak decay.

We here use a realistic Λ-nucleus wave function constructed from the YN G-matrix interaction (YNG potential[13,14]) with the $(0s)^n$ harmonic oscillator wave function for the nucleus. We also include the short-range correlation, the Nijmegen D correlation for OPE and the Gaussian soft cutoff correlation according to the baryon's quark wave function for DQ.

We found that for ${}^5_\Lambda$He, that the DQ amplitudes are dominant over OPE in $J = 0$ transitions (a_p, b_p, a_n) as well as ${}^3S_1 \to{}^3 P_1$ (f_p, f_n) transitions (Table 1). Also large $\Delta I = 3/2$ contributions are predicted for $J = 0$ transitions (a_p, b_p, a_n, b_n). Accordingly, the neutron induced decay rate Γ_n is enhanced from 0.025 (OPE only) to 0.206 (OPE+DQ) and thus improves the n/p ratio. This is still short of the experimental value as Γ_p is dominated by the $J = 1$ amplitudes from the strong one-pion tensor component. It was suggested that the kaon exchange may be important in reducing the $\Gamma_p(J = 1)$ [4].

For ${}^4_\Lambda$H, because no $J = 1$ $\Lambda p \to pn$ contributes, the DQ transitions become dominant. Both Γ_p and Γ_n are significantly enhanced by DQ: $\Gamma_p = 0.004$ (OPE) to $\Gamma_p = 0.047$ (DQ+OPE), and $\Gamma_n = 0.017$ (OPE) to $\Gamma_n = 0.126$ (DQ+OPE), and the total decay rates is predicted to be $\Gamma_{nm} = 0.174$. Although an indirect estimate [15] suggests $\Gamma_{nm} \simeq 0.17 \pm 0.11$, a direct measurement is very much anticipated.

For ${}^4_\Lambda$He, the neutron induced decay is suppressed, which seems consistent with experiment.

4. Weak $pn \to \Lambda p$ Production

The two-body weak interaction can be directly studied in the Λ production scattering: $pn \to \Lambda p$. The cross sections of such two-body processes were calculated in the meson exchange model[16], which claim $10^{-15} \simeq 10^{-16}$ barn. The cross section is dominated by the ${}^3S_1$ and ${}^3D_1$ channels and shows significant parity violation ($\simeq 25\%$).

Table 1
Calculated nonmesonic decay rates of ${}^{5}_{\Lambda}$He (in unit of Γ_Λ). $\Gamma_{nm} = \Gamma_p + \Gamma_n$ and $R_{np} = \Gamma_n/\Gamma_p$.

Channels			OPE	DQ	OPE + DQ
$p\Lambda \to pn$	${}^1S_0 \to {}^1S_0$	a_p	0.0002	0.0167	0.0188
	$\to {}^3P_0$	b_p	0.0031	0.0113	0.0026
	${}^3S_1 \to {}^3S_1$	c_p	0.1022	0.0548	0.2612
	$\to {}^3D_1$	d_p	0.0415	0	0.0415
	$\to {}^1P_1$	e_p	0.0346	0.0064	0.0207
	$\to {}^3P_1$	f_p	0.0093	0.0353	0.0763
$n\Lambda \to nn$	${}^1S_0 \to {}^1S_0$	a_n	0.0003	0.0407	0.0356
	$\to {}^3P_0$	b_n	0.0063	0.0069	0.0264
	${}^3S_1 \to {}^3P_1$	f_n	0.0185	0.0648	0.1437
		Γ_p	0.191	0.125	0.421
		Γ_n	0.025	0.112	0.206
		Γ_{nm}	0.216	0.237	0.627
		R_{np}	0.132	0.903	0.489

We have calculated the $pn \to p\Lambda$ cross section in the full six-quark cluster model with DQ+OPE weak transitions. We employ the standard quark cluster model for the initial NN and the final ΛN scattering wave functions[17]. The model contains the nonrelativistic quark kinetic energy, one-gluon exchange interaction (central + spin-spin + spin-orbit parts), and the meson exchange potentials for the nonets of scalar, pseudoscalar and vector mesons. The parameters in the meson exchange potential are tuned so as to reproduce the NN scattering phase shifts up to $E_{cm} \approx 350$ MeV. For the ΛN scattering, the $\Sigma N(I = 1/2)$ channels are always coupled.

The transition T matrix is calculated in the distorted wave Born approximation (DWBA) formulation. Our preliminary results consider only the weak transition to ΛN (not $NN \to \Sigma N$) and only the ${}^1S_0$ and ${}^3S_1$ ΛN final states. We found that the cross sections are of order of 10^{-16} barn, and are sensitive to the choices of the form factor for OPE and parameters in the ΛN final state interactions. Fig. 2 shows the (preliminary) results, which indicate that the OPE is dominated near threshold. The amplitudes are dominated by the $J = 1$ contribution. We also found that the PV/PC ratio depends on the ΛN energy rather strongly. It becomes as large as 60% at $E_{cm} \approx 50$ MeV. Inclusion of the ΣN channels and the higher partial waves have to be done further as well as study of dependencies on the parameters in the final state interactions. Further study is under way.

5. Conclusion

In conclusion, we would like to stress that nonmesonic weak decays of hypernuclei and weak hyperon productions are rich sources of interesting information on the nonleptonic

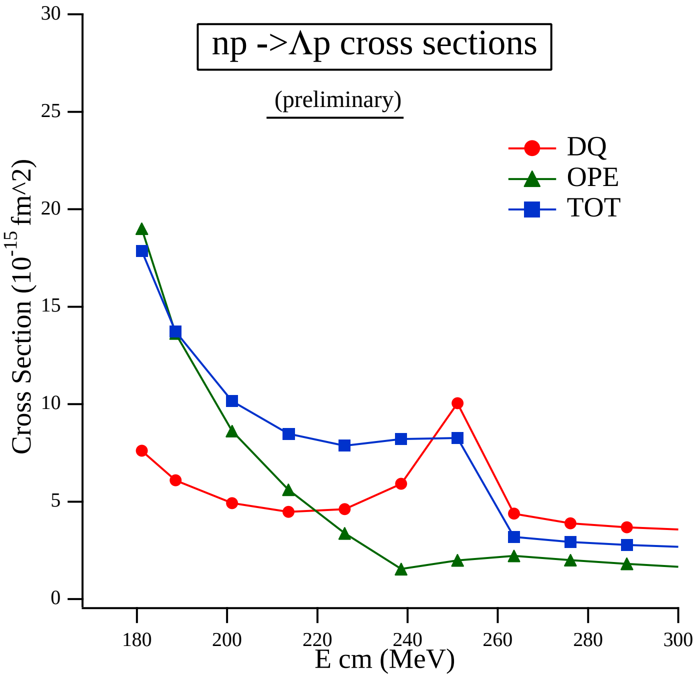

Figure 3. The $NN \to \Lambda N$ scattering cross sections.

weak interactions of hadrons. Here we have discussed the possibility of the direct quark contributions. We have found that the $\Delta I = 1/2$ rule may be significantly violated in hypernuclear weak decays, which can be tested in decays of the S-shell hypernuclei. It is crucial to have a high quality measurement of the decays of ${}^4_\Lambda$H.

Recently, we pointed out that soft π^+ emissions in weak decays of hypernuclei probe the $\Delta I = 3/2$ part of the nonmesonic weak decay[18]. We found that the soft π^+ can be emitted in the two-body process which is induced by the $\Delta I = 3/2$ weak interaction. The DQ transition potential predicts significant π^+ emissions in light hypernuclei. This opens a new possibility to check consistency in the weak decay mechanisms.

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